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The effect of geometry factors on fenestration energy performance and energy savings in office buildings

Irina Susorova*, Meysam Tabibzadeh, Anisur Rahman, Herek L. Clack, Mahjoub Elnimeiri

College of Architecture, Illinois Institute of Technology, 3300 South Federal Street, Chicago, IL 60616-3793, United States

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ABSTRACT

Although there have been multiple studies on window thermal properties in energy-efficient fenestration design, the effects of building geometry factors have been studied much less. The study presented in this paper evaluated the role of geometry factors, such as window orientation, window to wall ratio, and room width to depth ratio, on building energy performance in a commercial office building. A series of energy simulations were performed for six climate zones in the United States using a model of a room in a typical office building created in Design Builder, an energy analysis program, to evaluate total annual energy consumption. The simulation results were analyzed to find the combination of parameters yielding the lowest energy consumption and to define potential energy savings for office buildings located in various climate zones. The study showed that geometry factors affect energy consumption significantly in hot climates (Zones 2 and 3) and cold climates (Zones 6 and 7) but only marginally in temperate climates (Zones 4 and 5). Energy savings were on average 3% and 6% reaching a maximum of 10% and 14% in hot climates (Zones 2 and 3) and 1% in temperate and cold climates (Zones 4–7).

1. Introduction

For the past half century, new building construction has greatly increased. Building energy consumption also has grown significantly as building energy loads became larger due to the introduction of new systems of heating, air-conditioning, ventilation, and artificial lighting. Currently, energy use by buildings accounts for 40% of total primary energy produced in the US while energy consumption by commercial buildings is 18.4% of total primary energy [1]. In commercial buildings, energy is mainly used for heating (26.1%), lighting (14.7%), and cooling (9.3%) [1]. Building heating and cooling needs are affected by internal sources (electrical lighting, building equipment, and people) and external sources (solar radiation, air temperature, and wind) of heat gain and loss through facades. Transparent parts of building envelopes, or fenestration, are especially susceptible to large heat gain and loss because they are made from highly conductive materials and exposed to the direct heat gain from solar radiation. As of 1998, fenestration accounted for 22% of net heating and 32% of net cooling loads in commercial buildings [1].

To design efficient fenestration, one must account for the climate, building type, and the physical properties of glazing and framing materials, such as visual transmittance, solar heat gain coefficient, and thermal conductance. Much less considered but no less important, are building geometry factors, such as window orientation, window area, room dimensions, size and position of shading, and floor plan configurations. Geometry factors are defined by a building form, type, structural and HVAC systems used in common architectural practices. Building and fenestration geometry alone can affect energy consumption and therefore it is important to make objective energy conserving and daylighting decisions when defining a building's form, orientation, and enclosure type at the early stages of the building design process.

The main goal of this study was to evaluate the role of geometry factors on building energy performance in a commercial office building by performing energy simulations for various combinations of fenestration parameters and to define potential energy savings for buildings located in various climate zones. The study included six climate zones of the United States, Zone 2 hot (Houston, TX), Zone 3 warm (Los Angeles, CA), Zone 4 mixed (Seattle, WA), Zone 5 cool (Chicago, IL), Zone 6 cold (Minneapolis, MN), and Zone 7 very cold (Duluth, MN). Zone 1 very hot was not included in the calculations because it represents a very small portion of the United States territory including southern Florida and the Hawaiian Islands.

Multiple studies investigating energy-efficient fenestration considered geometry factors but few studies accounted for their role on building energy consumption. A study by Ghisi and Tinker [2] evaluated the potential for lighting energy savings in a 10-story office building located in hot and temperate climate zones by conducting

* Corresponding author at: Tel.: +1 312 882 0632.
E-mail addresses: isusorov@iit.edu, irinasusorova@gmail.com (I. Susorova).

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energy simulations to find the optimum window areas (window to wall ratio) for various room proportions and window orientations. A building with optimum window area demonstrated the lowest consumption of energy for cooling solar heat gained through fenestration and for artificial lighting. A similar study by Tzempelikos et al. [3] conducted a parametric analysis to investigate the effects of window to wall ratio and window orientation on daylighting, peak energy use, and overall energy consumption in an office building in Montreal. Another study by Ko [4] evaluated the improvement in energy performance of office buildings using daylighting by conducting energy simulations for four different climate zones using a model of a typical floor in a high-rise office building. The simulation results helped define the best combinations of fenestration parameters (window area, visual transmittance, heat transfer coefficient, and solar heat gain coefficient) optimizing daylighting and energy savings.

A number of studies researched the effects of fenestration parameters on heat transfer through building facades. A study by Chua and Chou [5] examined various parameters affecting building energy performance and researched the relation between cooling energy consumption and the envelope thermal transfer value (ETTV), a measure of heat flow through a building envelope that accounts for heat conduction through walls and solar heat gain through glazing. The study conducted energy simulations in the DOE-2.1E software using a model of a typical 12-story office building, square in plan, to evaluate the role of fenestration parameters, such as window to wall ratio, shading coefficient, heat transfer coefficient of opaque walls, and heat transfer coefficient of glazing on energy use. Similarly, a study by Motuzien and Juodis [6] examined the effect of window to wall ratio, window orientation, and glazing types on building energy use by evaluating energy performance of 100 alternative fenestration designs in an office building. A study by Johnson et al. [7] explored ways to maximize the daylighting benefits of fenestration and energy conservation in office buildings by performing energy simulations for five different climate zones and multiple fenestration parameters (visual transmittance, solar coefficient, heat transfer coefficient, window to wall ratio, and exterior shading). In research conducted by Carmody et al. [8], energy simulations were performed using a model of a typical room in a commercial office building to evaluate how fenestration parameters, including heat transfer coefficient, solar heat gain coefficient, visual transmittance, glazing type, window to wall ratio, window position, window shape, and orientation, affect building heating, cooling, lighting, and total energy consumption.

2. Methodology

To investigate the effects of geometry factors, a model of a single thermal zone in a typical office building was created in Design Builder, energy analysis software using the Energy Plus simulation engine. The model represented an office room located at a middle floor and midway along a building's width. Rooms at the top and bottom floors and corner rooms were not considered. The proposed model was rectangular in plan and was based on a typical office module of 1.5 m by 1.5 m that can fit into different plan configurations of a typical commercial building. The model had a floor-to-ceiling height of 2.75 m, a constant width of 6 m, and a depth which varied to accommodate different lease spans typically used in office buildings. The model's ceiling, floor, and three interior walls were adiabatic; heat transfer between the room and the exterior occurred only through the single exterior wall with glazing.

The thermal properties of the model's building materials were defined by the minimum requirements for energy performance set by the ASHRAE Standard 90.1 Energy Standard for buildings except low-rise residential buildings [9]. The model had a composite floor (concrete topping and metal deck above steel framing), a suspended acoustic tile ceiling, gypsum board internal partitions, and a metal-clad exterior wall (aluminum cladding with expanded polystyrene thermal insulation). While the thermal properties of the adiabatic elements were fixed, the minimum thermal properties of the opaque exterior wall differed depending on the requirements for each climate zone prescribed by the energy code (Table 1).

The model glazing consisted of double-pane glass with an air cavity and an aluminum frame with thermal breaks. A 4 cm wide aluminum frame had four 2.5 cm wide vertical dividers and constituted 10% of the total window area. The minimum thermal properties of the model glazing required by the energy code also varied with the climate zones (Table 1). Other settings related to the office model's building systems and activities were summarized in Table 2.

Table 2
Model settings.

Building HVAC system
HVAC system: variable air volume (VAV) system with terminal reheat
Cooling: chilled water coils, cooling system coefficient of performance 2.78, supply air temperature 10 °C, 1 h precooling
Heating: hot water coils, heating system coefficient of performance 0.8, supply air temperature 35 °C, 1 h preheat
Mechanical ventilation: intake fan with variable speed motor, 3 air changes per hour, total efficiency 78%, economizer, heat recovery, minimum ventilation 1 l/s-m^2
Thermostat set point: 21 °C for heating and 24 °C for cooling
Night setback temperature: 13 °C for heating and 32 °C for cooling
Auxiliary energy (fans and pumps): constant 36 kWh/m^2
Fuel: natural gas (heating) and electricity from grid (cooling)
Building schedule
Generic office occupancy: 1 person per 10 m^2
Activity schedule: 8 am to 7 pm on work days, closed on weekends and holidays (10 general US holidays)
Hot water consumption rate: 2 l/m^2/day, delivery temperature 43 °C
Building electrical loads
Office equipment: 8 W/m^2
Lighting equipment: 9.7 W/m^2 (building area method), 11 W/m^2 (space-by-space method)
Target illuminance: 430 lux
Lighting control: 3-stepped

Table 1
Minimum thermal properties of a building envelope.

Envelope properties	Climate zones					
	Zone 2 hot	Zone 3 warm	Zone 4 mixed	Zone 5 cool	Zone 6 cold	Zone 7 very cold
Heat transfer coefficient of steel-framed exterior wall assembly (W/m^2 K)	0.70	0.48	0.36	0.36	0.36	0.36
Heat transfer coefficient of fixed fenestration (W/m^2 K)[a]	4.25	3.68	3.13	3.13	3.13	2.56
Solar heat gain coefficient	0.25	0.25	0.40	0.40	0.40	0.45
Window to wall ratio	40%					

[a] Heat transfer coefficient of aluminum frame is 4.70 W/m^2 K.

Table 3
Total annual energy consumption in an office building in climate Zone 2.

Total annual energy consumption per unit area (kWh/m²/year)								
Room depth	Orientation	Window to wall ratio (WWR)						
		20%	30%	40%	50%	60%	70%	80%
6 m	North	145	135	134	136	137	139	141
	East	139	134	134	135	137	140	141
	South	130	127	127	128	129	131	132
	West	138	134	134	135	137	139	141
9 m	North	171	161	151	148	146	148	148
	East	162	155	150	147	146	148	148
	South	158	148	143	141	140	142	141
	West	161	154	149	146	145	147	147
12 m	North	175	167	159	152	148	148	148
	East	166	159	154	150	148	148	147
	South	162	153	147	143	142	142	141
	West	165	158	153	149	146	147	146
15 m	North	177	171	165	159	153	151	148
	East	168	161	157	153	150	149	148
	South	165	157	151	146	143	143	142
	West	168	161	156	152	149	148	147

The first evaluated parameter was window orientation; north, northeast, east, southeast, south, southwest, west, and northwest orientations were tested. Another tested parameter was window to wall ratio (WWR) which shows what percentage of an exterior wall area is occupied by glazing material. WWR is important as it affects the amount of available daylight and heat transfer between the exterior and interior of a building. Seven WWR values were tested for the constant window width of 6 m: 20% (0.55 m high window located 0.75 m above the floor level), 30% (0.8 m high window located 0.75 m above the floor level), 40% (1.1 m high window located 0.75 m above the floor level), 50% (1.4 m high window located 0.75 m above the floor level), 60% (1.6 m high window located 0.75 m above the floor level), 70% (1.9 m high window located 0.15 m above the floor level), and 80% (2.2 m high window located 0.15 m above the floor level). The maximum recommended value of WWR in commercial buildings according to the ASHRAE 90.1 Energy Standard is 40% for all climate zones; this value is used as the baseline case [9]. Any WWR greater than 40% is allowed only if a trade-off is provided showing improvements in energy performance over the baseline case.

The last parameter evaluated by this study was the ratio of room width to depth (*W*/*D* ratio), an important room geometry parameter which affects the interrelation between adiabatic interior walls and exterior walls and the distribution of daylight though a room's interior space. The width of a room's exterior wall determines the area exposed to heat transfer through the facade and the amount of received daylight; a room's depth determines the distance of daylight penetration. A wide and shallow room has a good daylight level and light distribution but high heat gain and loss through the large area of its exterior wall. In a narrow and deep room, a daylight level is lower but heat transfer through the small area of its exterior wall is much lower as well. The office room model tested four values of *W*/*D* ratio, 1:1, 1:1.5, 1:2, and 1:2.5, for the fixed room width of 6 m, which corresponded to room depths of 6 m, 9 m, 12 m, and 15 m respectively. The selected room depth values were based on typical lease spans in office buildings [4].

3. Results and discussion

It total, 1344 annual energy simulations were performed for 6 climate zones, 8 window orientations, 7 window to wall ratios, and 4 width to depth ratios. The simulations modeled lighting, heating, cooling, auxiliary (fans and pumps), hot water, and total energy consumption per year per square meter of office space.

The energy simulations for climate Zones 2 (Houston, TX) (Table 3 and Fig. 1) and 3 (Los Angeles, CA) (Fig. 2) demonstrated that total building energy consumption in a shallow room (room depth 6 m) lowers marginally when the window to wall ratio is increased from 20% to 40% and grows when the window to wall ratio is increased from 40% to 80%. Total consumption for other

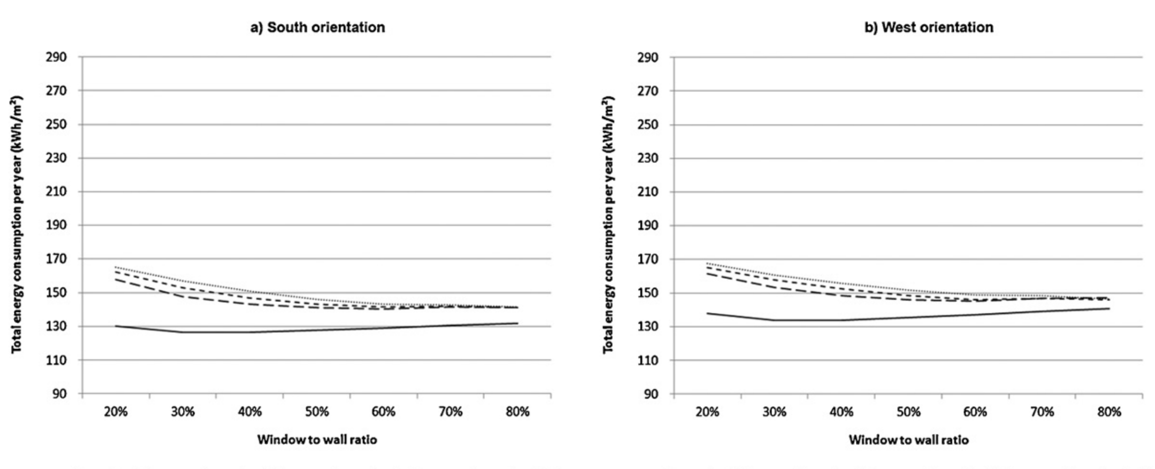

Fig. 1. Total energy consumption in climate Zone 2 for (a) south and (b) west window orientations.

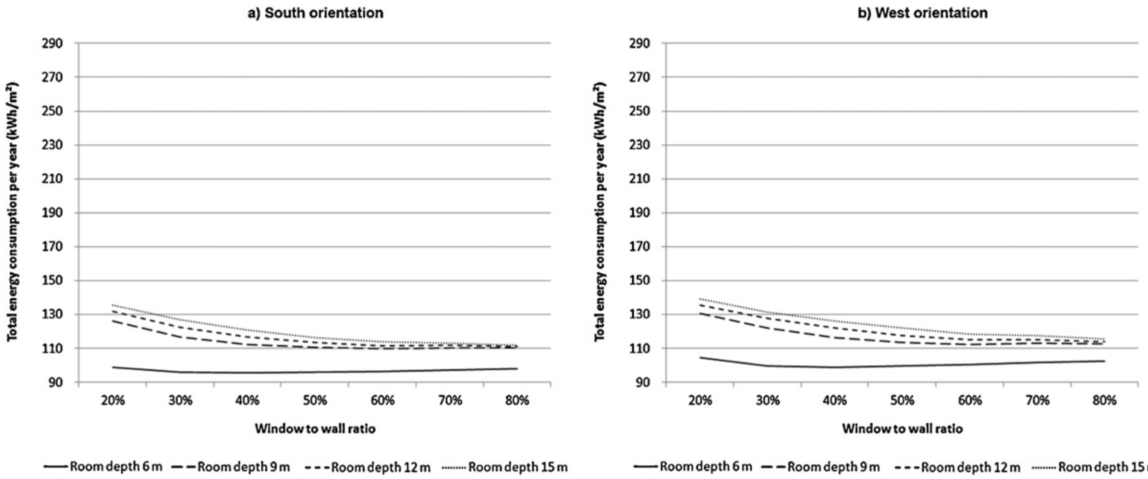

Fig. 2. Total energy consumption in climate Zone 3 for (a) south and (b) west window orientations.

Table 4
Total annual energy consumption in an office building in climate Zone 6.

Total annual energy consumption per unit area (kWh/m^2/year)								
Room depth	Orientation	Window to wall ratio (WWR)						
		20%	30%	40%	50%	60%	70%	80%
6 m	North	229	231	239	247	255	263	270
	East	222	225	230	236	243	249	255
	South	208	207	208	210	212	213	215
	West	222	225	231	237	244	250	256
9 m	North	230	231	230	232	236	242	247
	East	222	223	224	226	230	234	238
	South	214	210	208	208	208	210	210
	West	222	222	224	226	230	234	238
12 m	North	228	226	227	227	228	231	234
	East	219	219	219	220	222	225	227
	South	213	209	207	206	205	206	206
	West	219	218	219	220	222	225	227
15 m	North	224	224	225	225	225	227	228
	East	217	217	217	217	218	220	222
	South	213	209	207	205	204	204	204
	West	216	216	216	217	218	220	221

room depths (9 m, 12 m, and 15 m) steadily lowers as the window to wall ratio is increased from 20% to 80%. In contrast, in climate Zones 6 (Minneapolis, MN) (Table 4 and Fig. 3) and 7 (Duluth, MN) (Fig. 4), total building energy consumption grows steadily and significantly as the window to wall ratio is increased for all room depths and orientations except for south orientation where the effect is only marginal. The growth of energy consumption with the increase of the window to wall ratio is especially noticeable in shallow rooms but becomes less significant in deep rooms. In Zones 2, 3, 6, and 7, for all values of the window to wall ratio, energy consumption

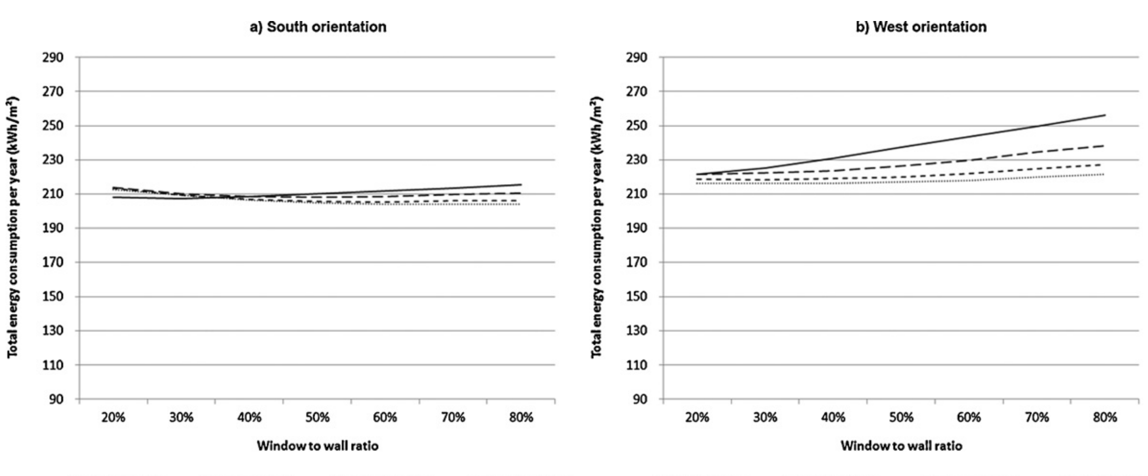

Fig. 3. Total energy consumption in climate Zone 6 for (a) south and (b) west window orientations.

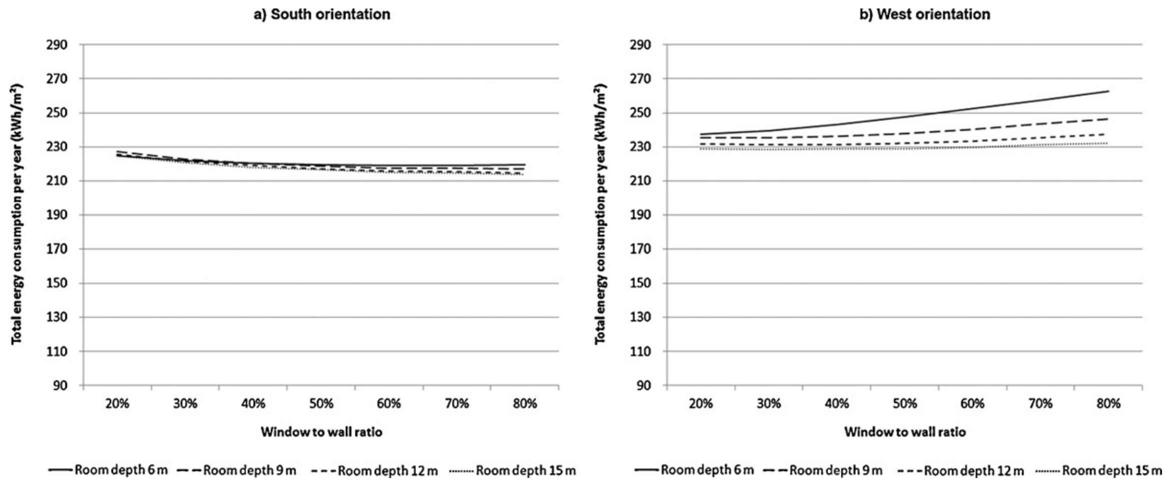

Fig. 4. Total energy consumption in climate Zone 7 for (a) south and (b) west window orientations.

Table 5
Total annual energy consumption in an office building in climate Zone 4.

Total annual energy consumption per unit area (kWh/m^2/year)								
Room depth	Orientation	Window to wall ratio (WWR)						
		20%	30%	40%	50%	60%	70%	80%
6 m	North	152	149	150	153	156	158	161
	East	145	143	143	145	147	149	151
	South	138	136	135	135	136	136	137
	West	145	144	145	147	149	152	154
9 m	North	160	157	154	152	152	154	155
	East	154	151	148	147	147	149	149
	South	147	143	141	140	139	140	140
	West	153	150	149	148	149	151	151
12 m	North	162	159	158	156	155	156	157
	East	155	153	152	151	151	152	152
	South	150	148	146	145	145	146	147
	West	154	152	151	151	151	153	154
15 m	North	160	158	156	155	153	153	151
	East	154	151	149	148	147	147	146
	South	150	145	143	141	139	139	139
	West	153	150	149	148	147	148	147

lowers with the increase in room depth from 6 m to 15 m and is the lowest for south orientation. In climate Zones 4 (Seattle, WA) (Table 5 and Fig. 5) and 5 (Chicago, IL) (Fig. 6), the change in building energy consumption is insignificant and does not appear to be affected by varying values for window to wall ratios, room depths and orientations.

In general, the highest reduction in total energy consumption in comparison with the baseline case was achieved with the window

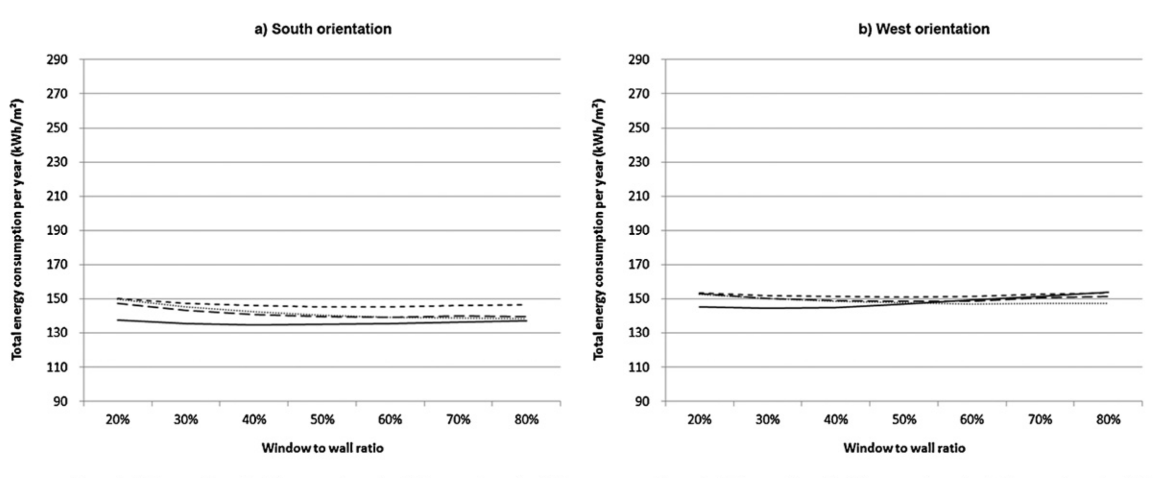

Fig. 5. Total energy consumption in climate Zone 4 for (a) south and (b) west window orientations.

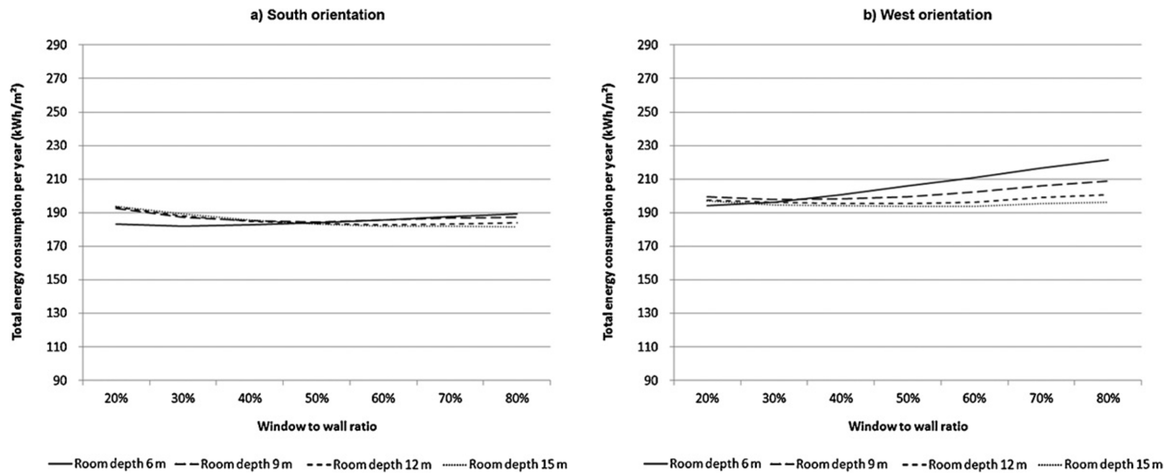

Fig. 6. Total energy consumption in climate Zone 5 for (a) south and (b) west window orientations.

to wall ratios of 30% (Zone 2), 40% (Zones 3 and 4), and 80% (Zones 5–7); room depths of 6 m (Zones 2–4) and 15 m (Zones 5–7); and north (Zones 2–4 and 7) and northwest (Zones 5 and 6) orientations.

Window to wall ratio has the highest effect on total energy consumption in deep rooms in hot climate zones (Zones 2 and 3) and in shallow rooms in cold climate zones (Zones 6 and 7) while it is relatively unimportant in medium-depth rooms. This observation is explained by the fact that in hot climates the need for artificial lighting is lower for rooms with large window area. In cold climates, large window areas contribute to a larger heat loss through windows in shallow rooms in which higher heat transfer through exterior surface is a predominant load on energy consumption. In such climates, small window area is preferable for north facades while larger area is better for south facades because heat gain from the sun can decrease the need for heating. In temperate climates (Zones 4 and 5), rooms with medium window area have the best energy performance.

Room depth (*W*/*D* ratio) has a significant effect on total energy consumption in rooms with small window areas in hot climates and in rooms with large window areas in cold climates; width to depth

Table 6
Combinations of window to wall ratio, room depth, and facade orientation parameters showing energy savings.

Climate	WWR (%)	Room depth			
		6 m	9 m	12 m	15 m
Zone 2	20	–	–	–	–
	30	S, SW	–	–	–
	50	–	All	All	All
	60	–	All	All	All
	70	–	All	All	All
	80	–	All	All	All
Zone 3	20	–	–	–	–
	30	–	–	–	–
	50	–	All	All	All
	60	–	All	All	All
	70	–	All	All	All
	80	–	All	All	All
Zone 4	20		–	–	–
	30	N, NE, E, W, NW	–	–	–
	50	–	All	All	All
	60	–	All	N, NE, E, SE, S, SW, NW	All
	70	–	N, SE, S	N, NE	All
	80	–	SE, S	N	All
Zone 5	20	N, NE, E, SE, S, SW, NW	–	–	–
	30	All	W	–	–
	50	–	S	N, NE, E, SE, S, SW, NW	N, NE, SE, S, SW, NW
	60	–	–	N, SE, S, SW	All
	70	–	–	S	N, SE, S, SW
	80	–	–	S	N, SE, S, SW
Zone 6	20	All	N, NE, E, W, NW	NE, E, W, NW	N, NE, E, W, NW
	30	All	NE, E, W, NW	N, NE, E, W, NW	N, NE, E, W, NW
	50	–	S	S, SE, SW	SE, S, SW
	60	–	S	S	SE, S, SW
	70	–	–	S	S
	80	–	–	S	S
Zone 7	20	N, NE, E, W, NW	N, NE, NW, W	NE, NW	N, NE, NW, W
	30	N, NE, E, SE, S, SW, NW	N, NE, E, W, NW	N, NE, W, NW	N, NE, E, W, NW
	50		SE, S, SW	SE, S, SW	SE, S, SW
	60	S	SE, S, SW	SE, S, SW	SE, S, SW
	70	S	S	SE, S, SW	SE, S, SW
	80	S	S	SE, S	SE, S, SW

Table 7
Total energy savings for different climate zones.

Room depth	Total energy savings (%)											
	Zone 2		Zone 3		Zone 4		Zone 5		Zone 6		Zone 7	
	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max
6 m	0.16	0.19	–	–	0.56	0.82	2.04	3.55	2.56	4.80	1.70	3.58
9 m	1.59	3.08	3.79	6.76	0.80	1.40	0.24	0.44	0.57	0.96	0.57	1.58
12 m	4.16	7.30	6.44	12.81	0.59	1.77	0.58	1.17	0.30	0.78	0.59	2.02
15 m	5.06	9.95	7.03	14.09	1.59	3.02	0.81	2.08	0.38	1.29	0.57	1.97
Average	2.74		5.75		0.89		0.92		0.95		0.86	

ratio only marginally affects energy consumption in temperate climates. In hot climates, shallow rooms have the best energy performance as less artificial lighting is required. In cold climates, deep rooms have the best energy performance because heat loss and gain through facade is minimal relative to heat gain from internal sources, such as electrical lighting and other building equipment. In temperate climates, medium-depth rooms have the best energy performance.

Window orientation only marginally affects energy consumption in all climates with south facade orientation always the best. In most cases, better energy performance for rooms with south window orientation in hot climates can be explained by south orientations being less exposed to direct sun heat gains since the sun mainly strikes horizontal surfaces during the day due to the high sun angle near the Equator. In cold climates, energy required by space heating is reduced because of heat gained by south facades exposed to the sun at low angles.

The simulations showed the combination of parameters that minimized energy consumption for a room in a typical office building. Annual energy consumption for each combination of parameter values was compared to energy consumption of the baseline case to evaluate energy savings. The baseline case model had the same properties as the main office model but the window to wall ratio was always set to 40% (maximum allowable window area prescribed by the energy standard) [9]. Table 6 shows for which combinations of window to wall ratio, room depth, and facade orientation parameters energy savings occurred. This can identify appropriate energy saving strategies to be used at the beginning of the building design process when a building does not have fully established geometry and multiple schemes have to be evaluated.

In climate Zones 2 and 3, main energy savings occurred in rooms of medium and high depths (9–15 m) with medium and large window areas (WWR of 50–80%) whereas in climate Zone 4 they occurred in rooms of medium and high depths with medium window area (WWR of 50–60%). In climate Zone 5, energy savings occurred in shallow rooms (6 m) with small window area (WWR of 20–30%) and in deep rooms (15 m) with medium window area (50–60%) while in climate Zone 6 they only occurred in shallow rooms with small window area. Finally in climate Zone 7, energy savings occurred in all north-oriented rooms with small window area (WWR of 20–30%) and in south-oriented rooms of medium and high depths (9–15 m) with medium and large window areas (WWR of 50–80%).

The study demonstrated that geometry factors have the highest effect on building energy savings in hot climates where savings on average are 2.74% (climate Zone 2) and 5.75% (climate Zone 3) but can reach as high as 9.95% for climate Zone 2 and 14.09% for climate Zone 3. Energy savings from geometry factors are marginal for temperate and cold climates and on average are 0.89% for climate Zone 4, 0.92% for climate Zone 5, 0.95% for climate Zone 6, and 0.86% for climate Zone 7. The energy savings are summarized in Table 7.

4. Conclusion

This study demonstrated that optimizing building and fenestration geometry parameters (window to wall ratio, window orientation, and width to depth ratio) can decrease building energy consumption in office buildings and achieve energy savings in all climate zones. The highest energy savings with fenestration geometry (up to 14% overall savings) can be achieved in hot climates while energy savings in temperate and cold climates are marginal.

- In general, shallow rooms have the best energy performance for all orientations and window sizes in hot and temperate climates while deep rooms perform the best in cold climates.
- In hot and temperate climates, the best energy performance occurs in shallow rooms with medium-sized windows and in deep rooms with large windows. In cold climates, the best performance occurs in shallow rooms with small windows and in deep rooms with medium-sized windows.
- Rooms oriented south have generally the best energy performance in all climates.
- In hot and temperate climates, the lowest energy consumption occurs for north-oriented rooms with large windows and for rooms with small windows oriented toward south. In cold climates, the lowest energy consumption occurs for south-oriented rooms with large windows.

This study results indicate that geometry parameters should be carefully addressed when designing new office buildings or retrofitting old ones. Proper use of building and fenestration geometry parameters combined with other fenestration elements, such as shading, energy-efficient glazing, room geometry, and responsive building systems will noticeably minimize building energy use and improve building performance.

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References

[1] Building Energy Data Book, United States Department of Energy. http://buildingsdatabook.eren.doe.gov/default.aspx, 2011 (accessed 01.02.12).
[2] E. Ghisi, J.A. Tinker, An ideal window area concept for energy efficient integration of daylight and artificial light in buildings, Building and Environment 40 (2005) 51–61.
[3] A. Tzempelikos, A.K. Athienitis, P. Karava, Simulation of facade and envelope design options for a new institutional building, Solar Energy 81 (2007) 1088–1103.
[4] D.H. Ko, Fenestration guideline for energy and daylight efficiency: evaluation and prediction of performance in office buildings. Doctorate Dissertation, Illinois Institute of Technology, Chicago, 2009.
[5] K.J. Chua, S.K. Chou, An ETTV-based approach to improving the energy performance of commercial buildings, Energy and Buildings 42 (4) (2010) 491–499.

[6] V. Motuzienė, E.S. Juodis, Simulation based complex energy assessment of office building fenestration, Journal of Civil Engineering and Management 16 (3) (2010) 345–351.
[7] R. Johnson, R. Sullivan, S. Selkowitz, S. Nozaki, C. Conner, D. Arasteh, Glazing energy performance and design optimization with daylighting, Energy and Buildings 6 (1984) 305–317.
[8] J. Carmody, S. Selkowitz, E.S. Lee, D. Abasteh, T. Willmert, Windows Systems for High-Performance Buildings, W. W. Norton & Company, Inc., New York, 2004.
[9] ASHRAE, Standard 90.1 energy standard for buildings except low-rise residential buildings, in: American Society of Heating, Refrigeration, and Air-Conditionning Engineers, 2010.